Lunar Dust
and
Dusty Plasma Physics

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Summary

- **A brief review of the Earth-Moon plasma environment.**
- **Discussion of how the dusty plasma environment links to exploration.**

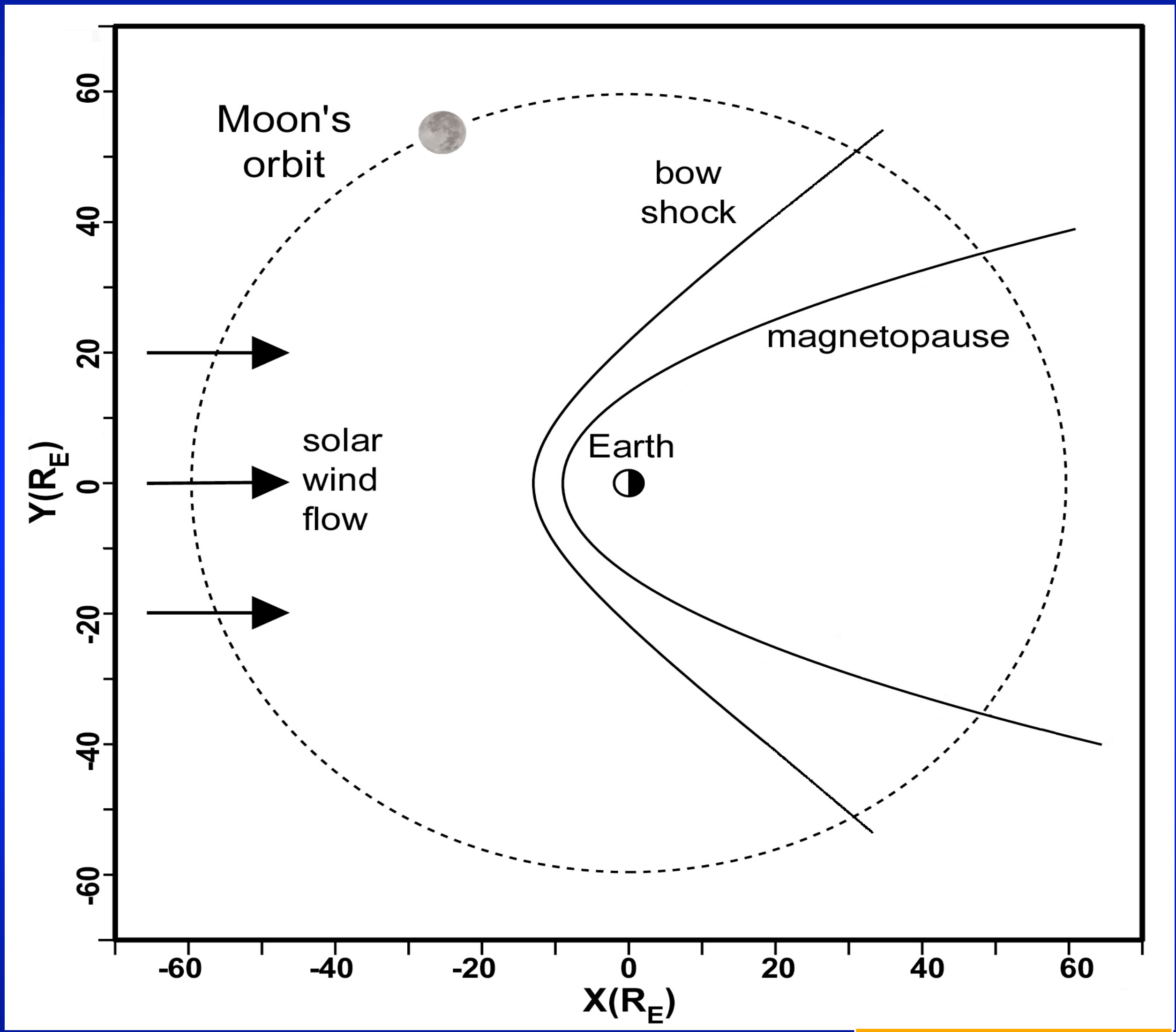
Exposure Dilemma

- If a person or instrument were standing on the Moon, what sort of environment or "weather" would one experience?
- There are many answers (e.g., cosmic rays are fierce).
- In this session we are focusing on direct exposure to space plasmas.

Direct Interaction with Sun, Earth, and Meteoroids

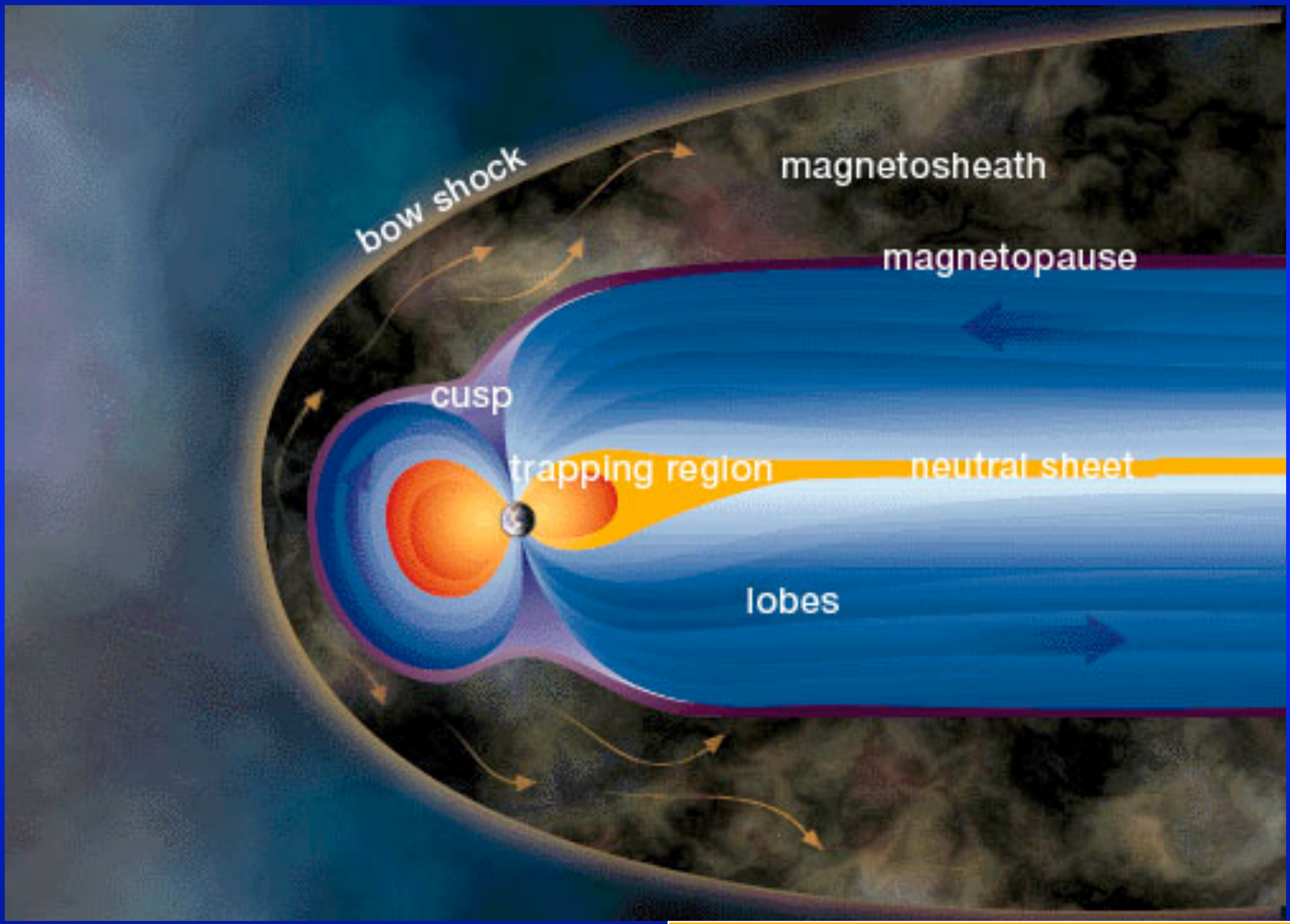
- Direct Solar Wind
- Earth's magnetotail and plasmasheet
- Wake of the Moon
- Transient Na "atmosphere" during Leonid showers.

Direct Solar Wind



D. Shriver (2005)

Earth's Magnetotail & Plasmasheet



Mike Hapgood (2007) *Ann. Geophys.* **25**, 2037

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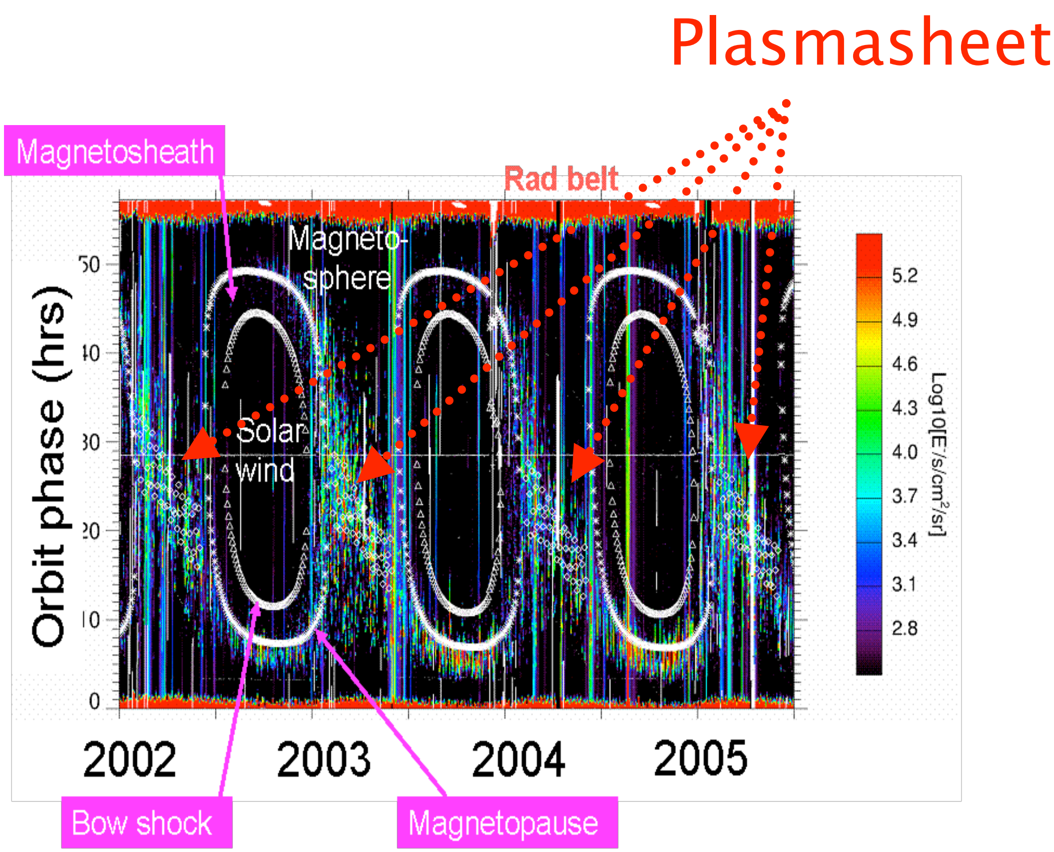
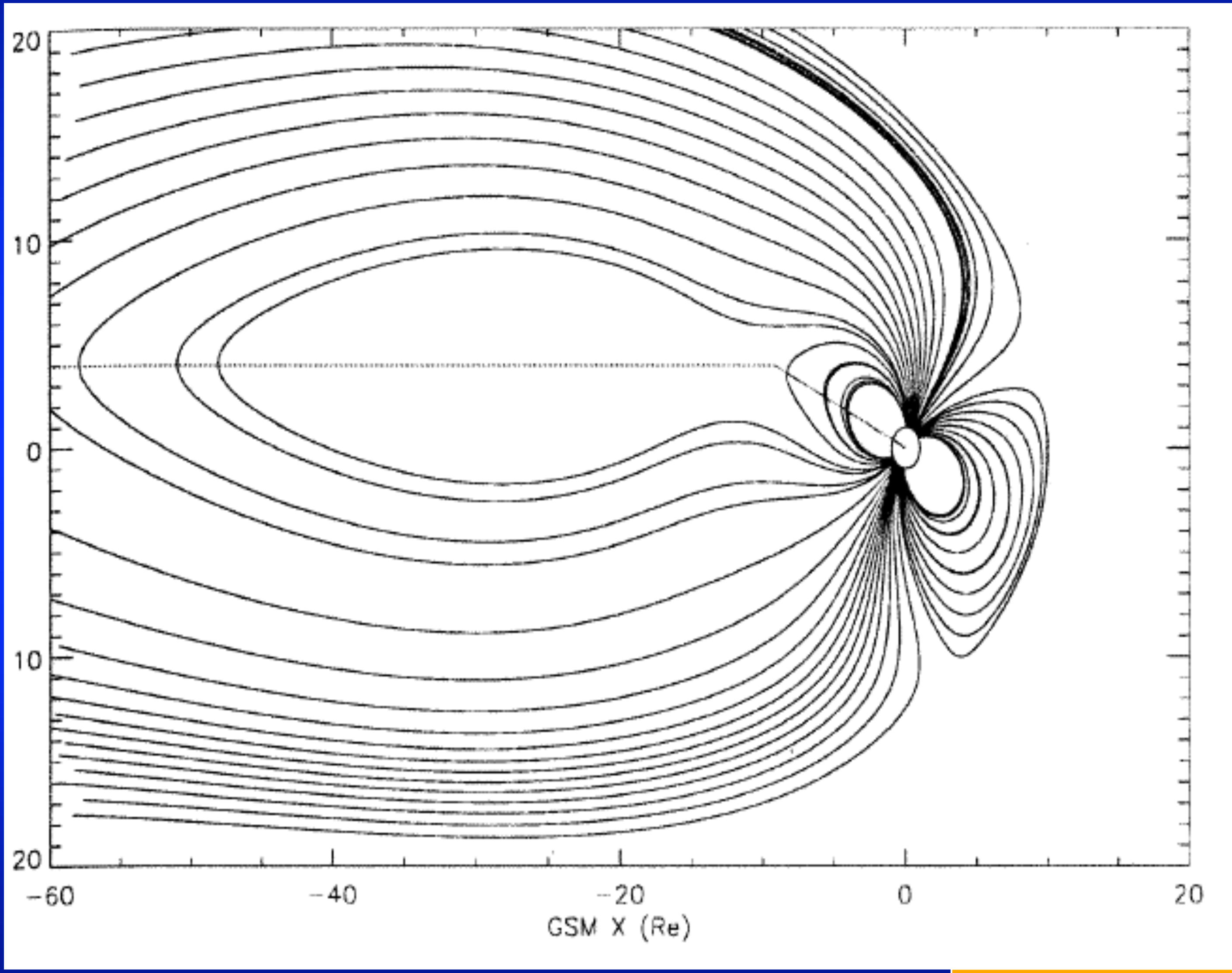
ESA's Cluster Observation of Plasmasheet



Summary of 50 keV electrons seen by ESA's 4 Cluster Satellites

Moon’s Interaction with Plasmasheet



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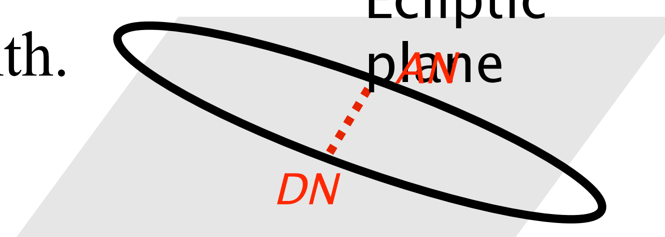
Rutherford Appleton Lab

Moon's Interaction with Plasmasheet

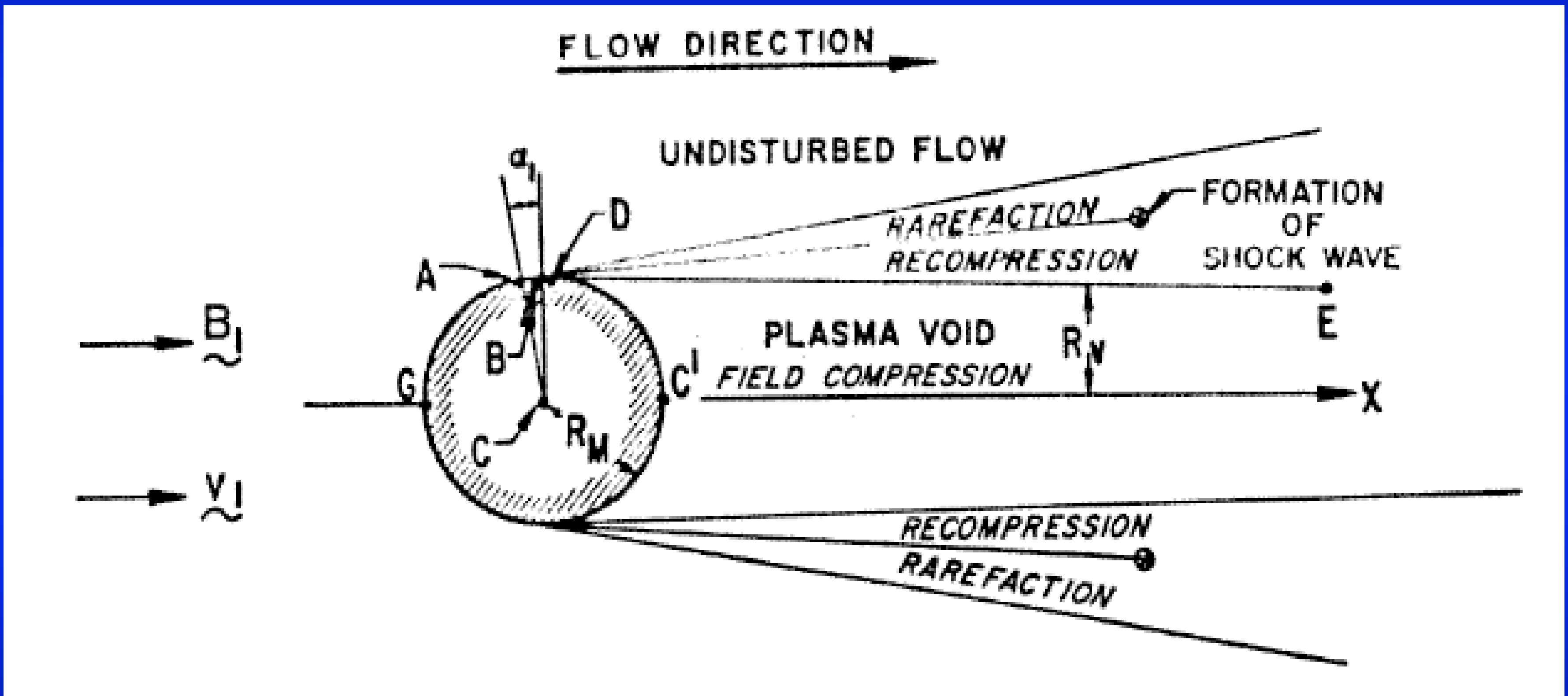
- The Moon occasionally encounters dense hot plasma of the Earth's plasmasheet.
- Lunar surface can build up a charge under these conditions. (A "hair-raising" event for astronauts?)
- Observed by Lunar Prospector.
- Moon crosses Earth's magnetotail around Full Moon.
  - Approx. 4 to 5 days per month.
  - ± 5 R_E wrt Ecliptic.
  - There is an 18.6 yr cycle in lunar charging.



The Wake of the Moon has Unexpected Features

- **"Behind the Moon" is also relevant to dust dynamics on the back side (away from the Sun).**
- **There exists a plasma void ("wake") during the Moon's orbit about the Sun.**
- **The interplanetary magnetic field, however, <u>increases</u> in the wake region of the Moon.**

Wake of the Moon (1968)



Wolf R.A. *JGR* **73** 4281 (1968)

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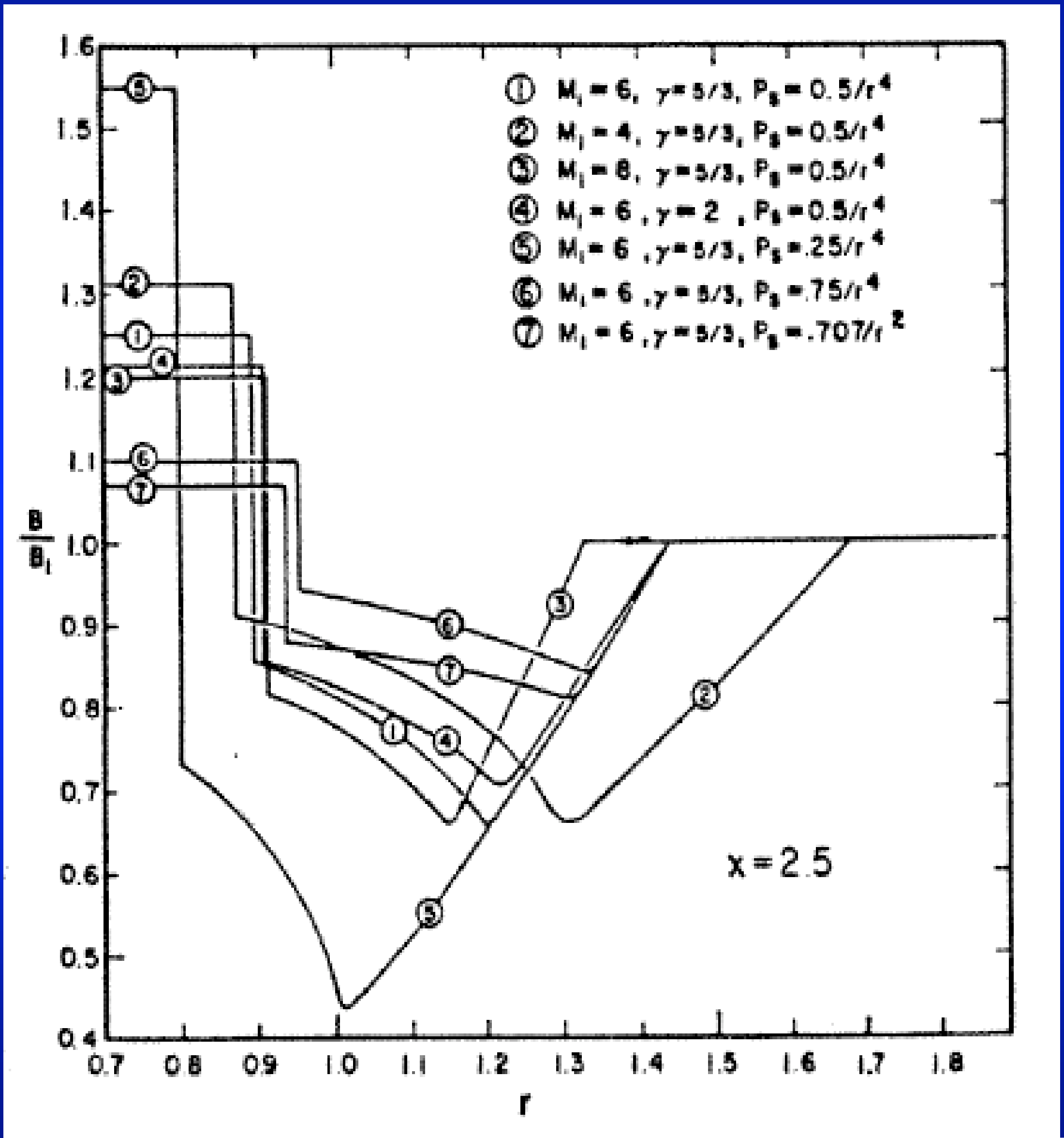
Magnetic Field in Wake of the Moon



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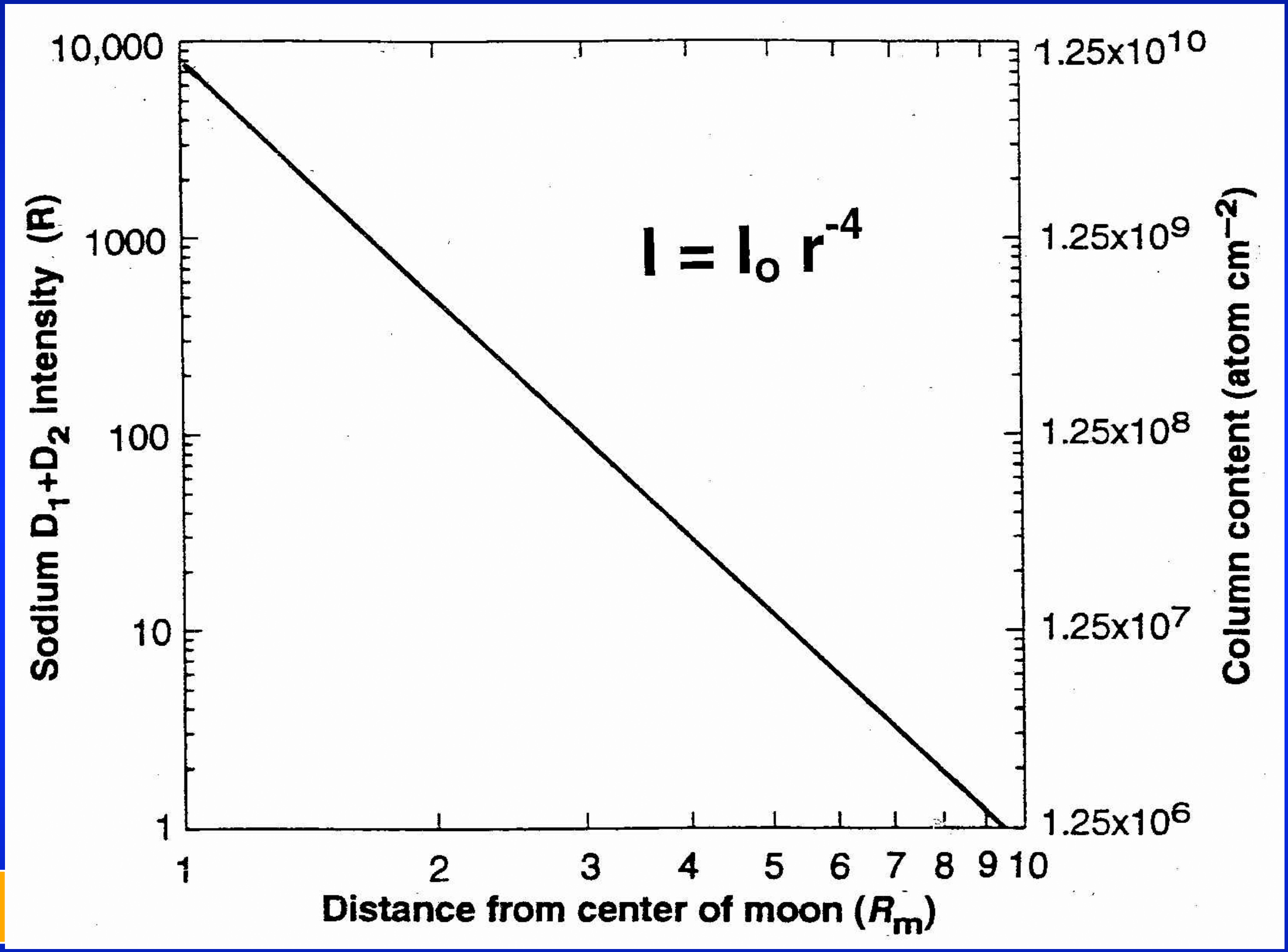
Wolf R.A. *JGR* **73** 4281 (1968)

Direct Interaction with Leonids



Boston University

Transient "atmospheric" Na tail can be seen downwind for 100's of lunar radii.

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Flynn, B., and Mendillo, M., (1993) *Science* **261**, 184

Direct Interaction with Leonids

- Equations for Na lines.
- Sodium fluorescence intensity $I(r, \chi)$ is a powerlaw formula:

$$I(r, \chi) = I_o\, r^{-\alpha}$$

where I_o

$$I_o = (1 + 6\cos 8\chi),$$

is measured in kilorayleighs, χ is the solar zenith angle (latitude), and α is

$$\alpha = 2(1 + \cos 3\chi).$$

Consequence: A Dusty Regolith Interacting With Space Plasmas

- **Question – How does lunar dust interact with space plasmas?**
- **Answer – Dusty plasma physics.**

Let's Define a Dusty Plasma.

- Plasma is ubiquitous in the Universe.
  - It is a fourth state of matter (besides solid, liquid, gas).
  - It is an **ionized or charged gas** that is highly conductive.
- Dust grains are also quite common in the Universe.
  - Dust is the powder form of solid matter.
  - Dust can be readily charged just like elementary particles.
  - Dust can be picked up by a passing plasma (pickup dust) or kicked up by sputtering (and vulcanism).
  - Unlike elementary particles or ionized nuclei (CRs):
    - It has a different charge-to-mass ratio.
    - It retains its material properties as solid matter (dielectric and magnetic) with **surface potentials**. Scalar properties become tensors.
- Dusty plasmas are studied in the rings of Jupiter and Uranus, etc. We have come a long way since Apollo.

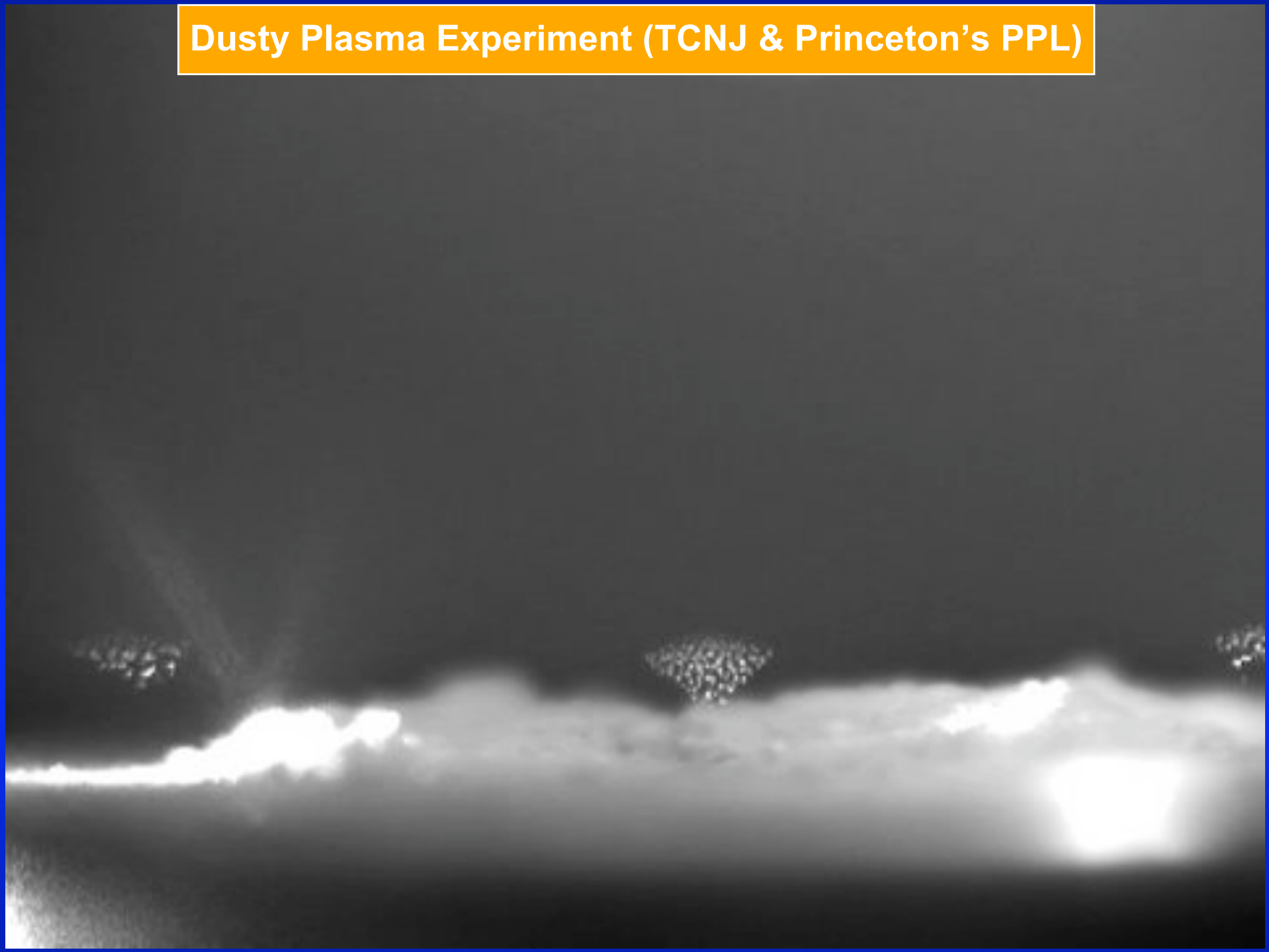
Let's Define a Dusty Plasma (2).

- Dusty plasma is a plasma that suspends nanometer or micrometer-sized particles.
- Occurrence
  - Space plasmas
  - Industrial applications (on Earth)
- Properties
  - Temperature

Dusty Plasma Constituent	Temperature	Temperature
Dust temperature	10 K	~ 10^{-3} eV
Molecular temperature	100 K	~ 10^{-2} eV
Ion temperature	1,000 K	~ 10^{-1} eV
Electron temperature	10,000 K	0.86 eV

  - Electric Potential: $\pm$ 1-10 V (or kV's in relativistic cases)

Example of a Dusty Plasma.



Dust clouds form where gravitation & electromagnetism offset (levitation). Three appear above at equilibrium points determined by chamber geometry.

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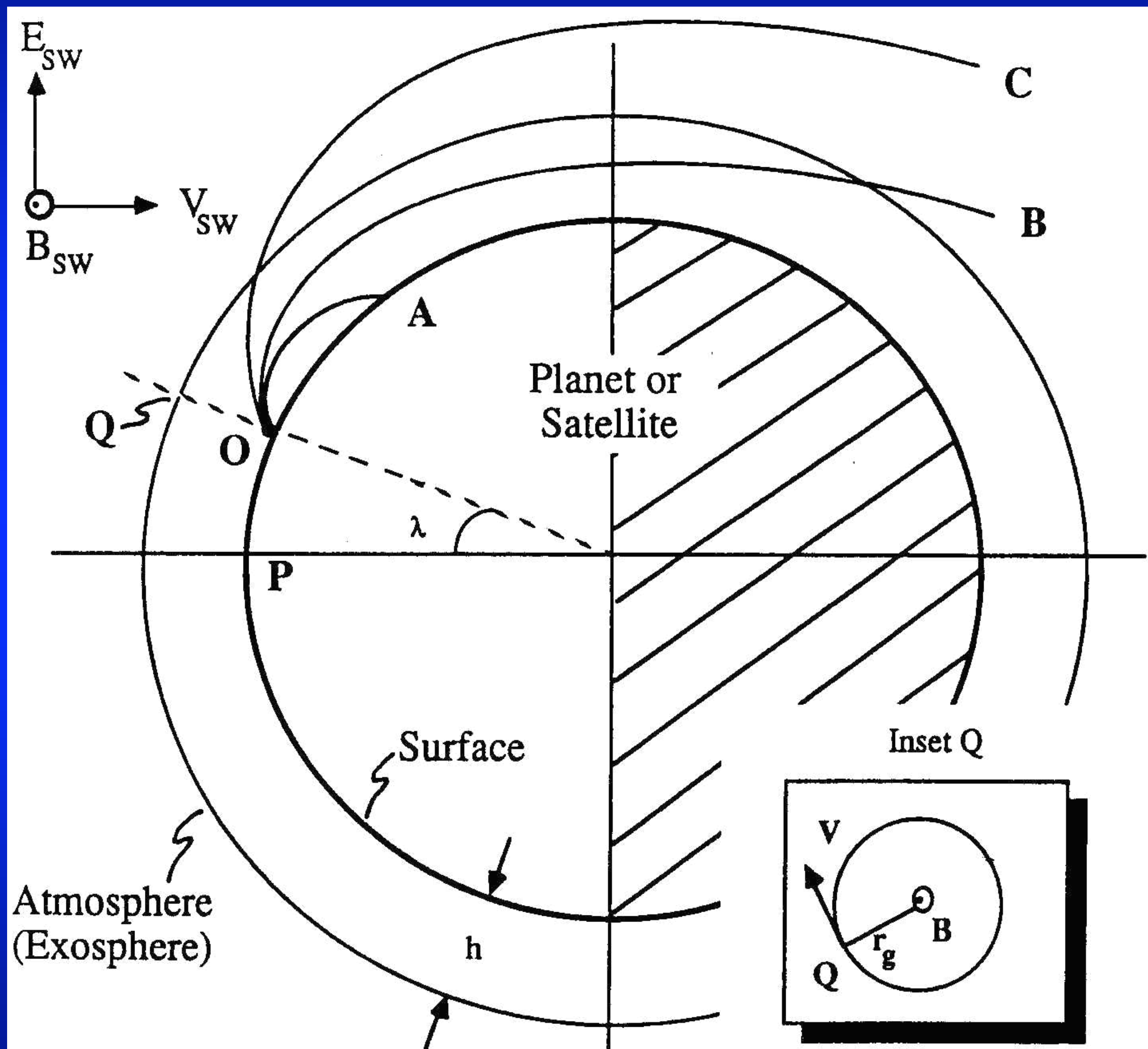
Relevance to Lunar Exploration

- Dust transport
  - Levitation and transport of lunar dust has been under study since the Apollo era.
  - Dust mitigation is hence a major environmental issue.
  - Dusty plasma physics is key to dust transport.
    - This is more than electrodynamics and Leyden jars.
    - Involves **MHD and plasmas** – the physics of highly conductive ionized gas flow (fluid mechanics plus electromagnetism).
    - Involves the transport of charge via pickup dust in the presence of space plasmas and magnetic fields.
- Electric potentials and charging
  - Moon's electric potentials are dynamic and time-dependent. These need to be modelled and measured.
  - Potentials produce electric fields (which transport dust).
  - Risk involves charging/discharging in lunar ops.

Dusty Plasma Levitation Geometry



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Dusty Plasma Levitation Dynamics

- Lorentz force $\boldsymbol{F} = q(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}x\boldsymbol{B})$
- Lorentz transformation $\boldsymbol{E} = \boldsymbol{E}' - \boldsymbol{V}x\boldsymbol{B}$
- Ohm's law $\boldsymbol{J} = \sigma\boldsymbol{E}' = \sigma(\boldsymbol{E} + \boldsymbol{V}x\boldsymbol{B})$
- Plasma (Conductivity $\sigma\rightarrow\infty$) $\boldsymbol{E}_{SW} = -\boldsymbol{V}_{SW}\ \boldsymbol{x}\ \boldsymbol{B}_{SW}$
- $\boldsymbol{F} = \boldsymbol{m}\boldsymbol{a}$ (gravity + EM) $\ddot{\boldsymbol{r}} = -\frac{GM\boldsymbol{r}}{r^3} + \frac{q}{m}(\boldsymbol{E} + \frac{\dot{\boldsymbol{r}}}{c}x\boldsymbol{B})$
- Lunar surface potential Φ_o $\Phi_o = kQ / r_o$
- Lunar electric field $\boldsymbol{E}_o = -\nabla\Phi_o = \Phi_o\ \boldsymbol{r}/r^3$
- Ambient electric fields $\boldsymbol{E}^*$ $\boldsymbol{E} = \boldsymbol{E}_o + \boldsymbol{E}^*$
- Levitation dynamics: $\ddot{\boldsymbol{r}} = -\frac{\mu\boldsymbol{r}}{r^3} + \frac{Z}{m}(\boldsymbol{E}^* + \frac{\dot{\boldsymbol{r}}}{c}x\boldsymbol{B})$

  (Dusty plasma $Z=Z_{dust}q$) $\mu = (GM - \frac{Z}{m}\Phi_o)$

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Electromagnetism + Gravitation

Space Plasmas & MHD Physics On The Moon

- **There is more: MHD physics (Alfvén).**
- ***Magneto*(magnetic field)-*hydro*(liquid)-*dynamics*(motion).**
- **To gravitation and electromagnetism we add:**
  - **Fluid mechanics**
    - **This means the Navier-Stokes equations (nonlinear).**
    - **Plus Maxwell's equations (modified Ohm's Law, etc.).**
- **Because MHD is a *fluid* theory, it <u>cannot</u> be used for *kinetic* phenomena (Boltzmann Eq.) – more on this later.**

3-Dimensional MHD Equations

$$\frac{\partial \vec{A}}{\partial t} - \vec{v} \times \nabla \times \vec{A} = -\eta \nabla \times \nabla \times \vec{A} \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{2}$$

$$\frac{\partial P}{\partial t} + \nabla \cdot (P\vec{v}) = (\gamma - 1)\left[-P(\nabla \cdot \vec{v}) + \eta J^2 - \frac{1}{R_e}\mathbf{W} : \nabla \vec{v}\right] \tag{3}$$

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}\right) = -\nabla P + \vec{J} \times \vec{B} - \frac{1}{R_e}\nabla \cdot \mathbf{W} \tag{4}$$

Jia X. *et al.* (2008) *JGR* **113**, A012748

3-D MHD Equations – FLASH Code

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) = -\nabla \left(p + \frac{B^2}{2} \right) + \rho \mathbf{g}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot \left[\mathbf{v} \left(\rho E + p + \frac{B^2}{2} \right) - \mathbf{B}(\mathbf{v} \cdot \mathbf{B}) \right] = \rho \mathbf{g} \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0$$

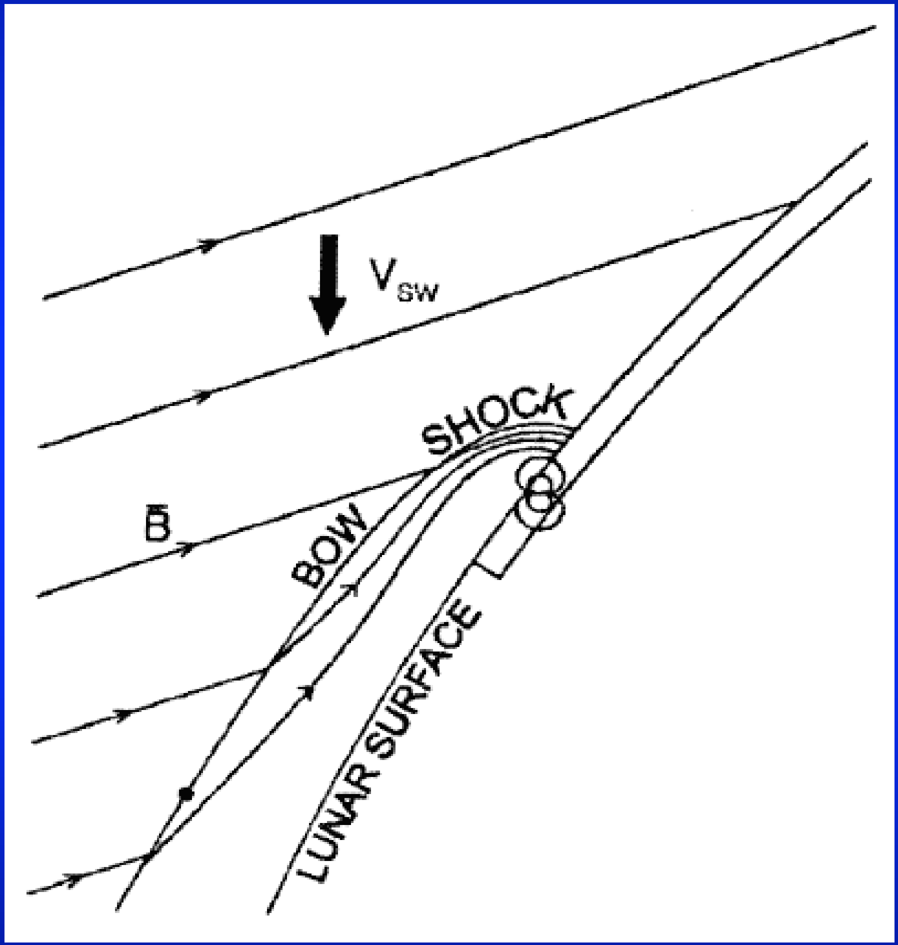
$$E = \frac{1}{2} v^2 + \varepsilon + \frac{1}{2} \frac{B^2}{\rho}$$

Gombosi, *Physics of the Space Environment* (1998)

An Example When MHD Does Work on the Moon

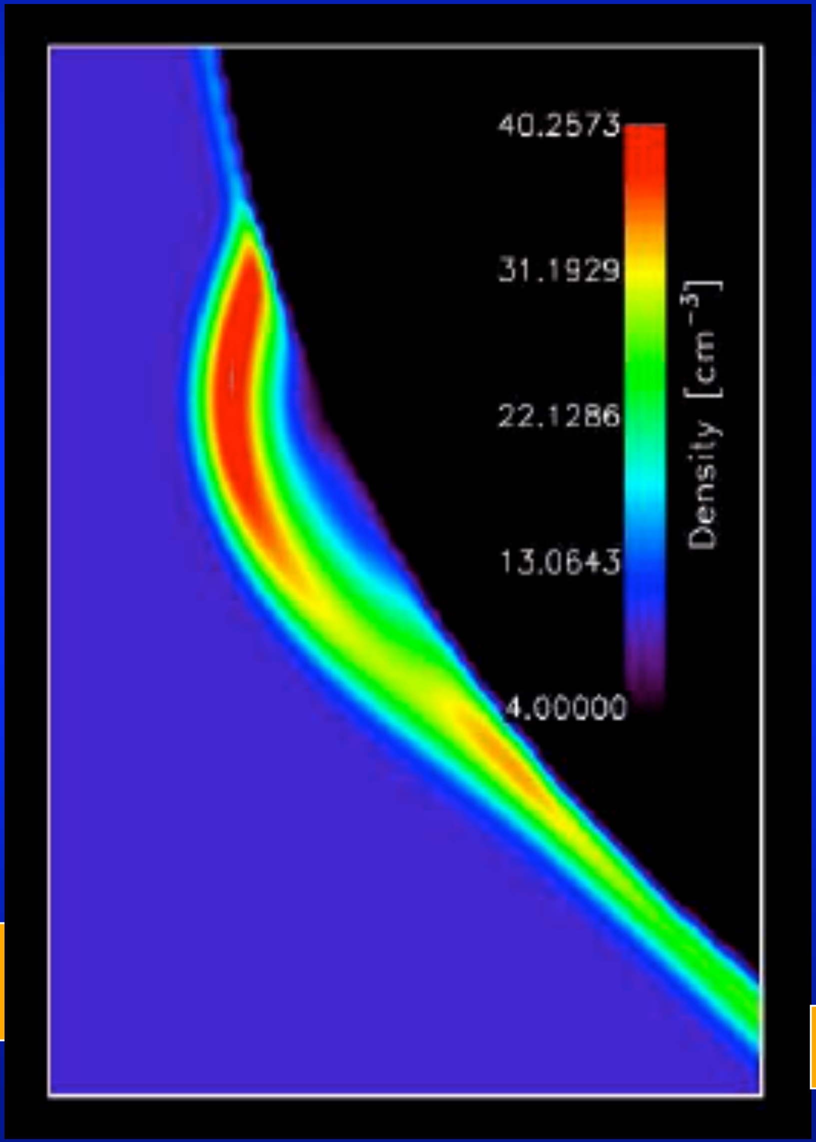
- The Moon has no appreciable magnetic dipole field – hence no magnetosphere.
- However, the Moon has magnetic anomalies imbedded in its surface.
- These anomalies can creat mini-bow shocks.
- They can be modelled with mini-dipoles.

Example of mini-Magnetospheres on the Moon (Lunar Prospector)



Lin *et al.* (1998) *Science* **281**, `480

2.5D MHD Sim of mini-Magnetospheres on Moon's Surface



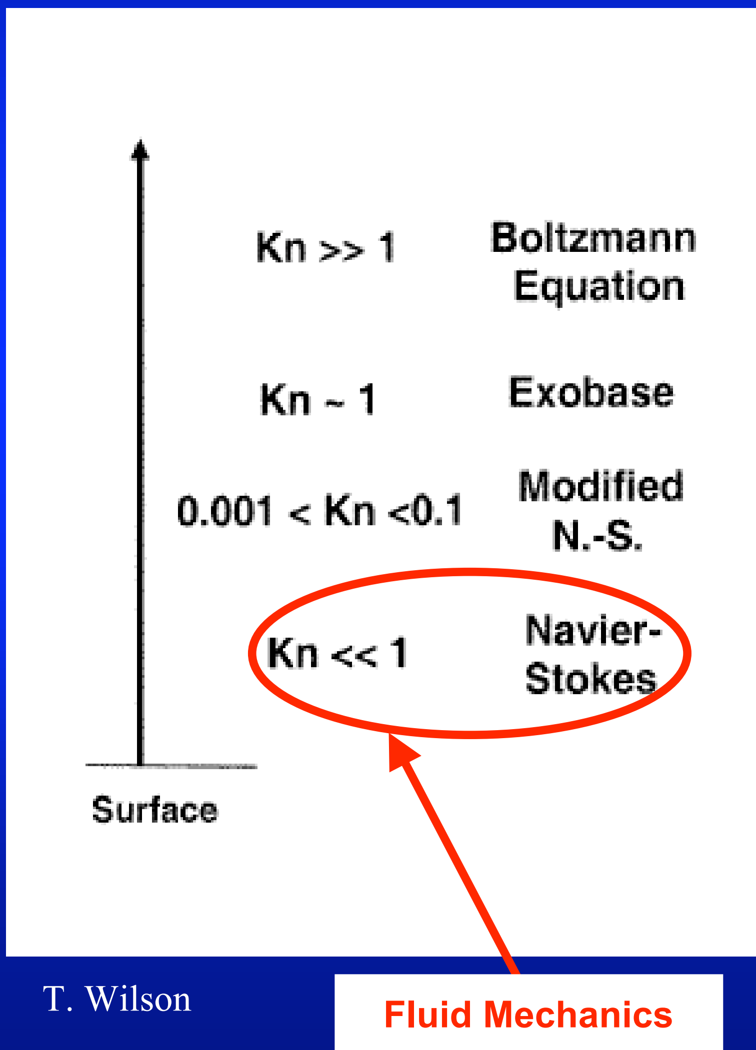
Harnett & Winglee (2002)
JGR **107**, A009241

Univ. of Washington

When Does MHD Not Work?

- MHD no longer works when the Navier-Stokes equations are not applicable.
- This happens when the existence of discrete particles becomes important.
- That requires the kinetics of Boltzmann transport theory.
- The Moon has both.
- Now we come to Knudsen Numbers (1911).

The Moon has an exosphere. What is an exosphere?



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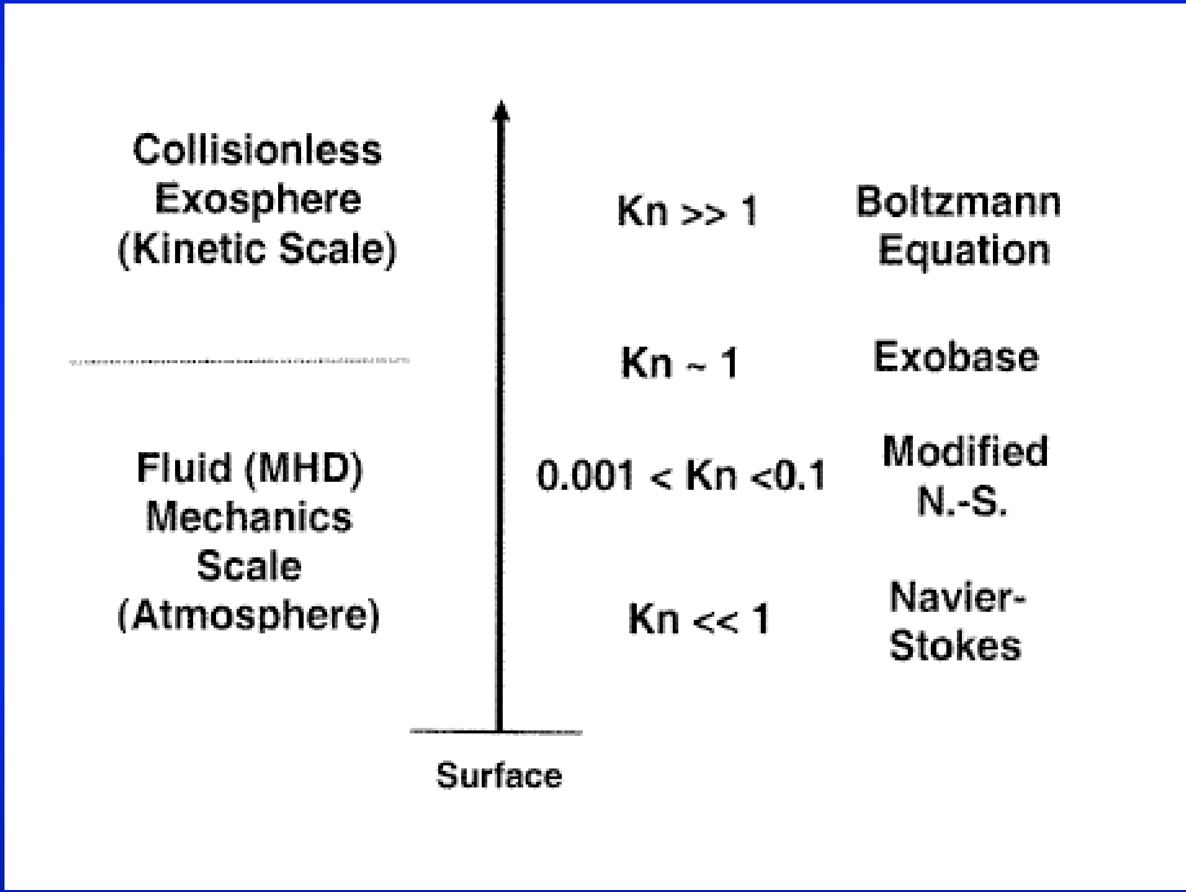
- The definition varies:
- Knudsen # is Kn≥1.
- Mean free path exceeds scale height.
- Consequences Kn>1:
- Discrete Simulation Monte Carlos (DSMC).
- For larger length scales (e.g. Earth radii), MHD used for bow shocks, geotail dynamics.

How Do We Define the Moon's Exosphere?



We define the Moon's exosphere as beginning with Kn ~ 1.

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Conclusion

- **We have reviewed some of the space physics related to the transport of dust on and about the Moon. The physics is understood.**
- **What is lacking?**
  - **The physics is very often nonlinear.**
  - **The Navier-Stokes problems are unsolvable.**
  - **This requires models, simulations, and Monte Carlos.**
  - **Models require laboratory study, flight data, and actual measurements.**
- **Both simulations and flight measurements are essential to the success of lunar exploration.**

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